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Eddy current analysis and optimization of fast scanning magnet for a proton therapy system[☆]

Xu Liu, Bin Qin*, Kaifeng Liu, Wei Chen, Zhikai Liang, Qushan Chen, Dezhi Chen, Mingwu Fan

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan 430074, Hubei, China

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ABSTRACT

Proton therapy is now recognized as one of the most effective radiation therapy methods for cancers. A proton therapy facility with multiple gantry treatment rooms is under development in HUST (Huazhong University of Science and Technology), which is based on isochronous superconducting cyclotron scheme. In the beam line, the scanning system spreads out the proton beam on the target according to the complex tumour shape by two scanning magnets for horizontal and vertical scanning independently. Since these two magnets are excited by alternating currents and the maximum repetition frequency is up to 100 Hz, eddy currents and losses are expected to be significant. Slits are proven to be an effective way to reduce the eddy currents. To evaluate the heat distribution due to eddy losses in the pole end of the scanning magnet, the transient electromagnetic analysis and steady-state thermal analysis are performed. This paper describes design considerations of the scanning system and mainly analyses the eddy current effect of the scanning magnets. Different coil shapes and slit arrangements are simulated and compared to obtain the optimal configuration. The maximum temperatures of two magnets are optimized below 70 °C. In addition, the lag effect due to eddy currents is also discussed.

1. Introduction

Nowadays, proton therapy becomes an effective method for radiation cancer treatment. Compared with the traditional X-ray or gamma-ray therapy, proton beam has a controllable depth-dose distribution with its 'Bragg Peak' dose characteristic.

Due to the specific features of compactness, low power consumption and high availability, the superconducting cyclotron has been well demonstrated and applied to proton therapy facilities [1,2]. A proton therapy facility based on an isochronous superconducting cyclotron is under development in HUST, by a collaborative team from HUST, CIAE (China Institute of Atomic Energy), Tongji Hospital and Union Hospital affiliated to HUST. For HUST proton therapy facility (HUST-PTF), a 250 MeV proton beam with 500 nA will be extracted from a superconducting cyclotron. After passing through the energy selection system(ESS) in which the energy will be modulated in the range of 70–240 MeV, it will be switched and delivered to three treatment rooms (two gantry rooms and one room with fixed beam line) [3].

In general, depending on the position of the scanning magnets, upstream or downstream scanning schemes are used to implement active pencil beam scanning [4,5]. For the gantry beam line of HUST-PTF, the downstream scanning scheme was adopted [6]. To mitigate the skin dose accumulation caused by non-parallel beam, the SAD (Source to axis distance) is designed to be 2.8 m. A large field size of $30 \times 30\ \mathrm{cm}^2$ can be achieved, while keeping the aperture of the last dipole to be the same dimension as other dipoles in the beam line. In addition, for the downstream scanning, the correlation between the beam spot position and scanning magnet current is also linear, which can reduce the difficulty of treatment planning.

Scanning magnets play a key role in the pencil beam scanning system, which should meet three requirements by clinical specifications:

(a) The magnetic field shall be strong enough to deflect the proton beam with maximum energy to cover the required radiation field.
(b) The beam position accuracy, reproducibility and stability must be guaranteed to meet the dose uniformity requirements and achieve precise treatment.
(c) Fast scanning speed is essential for a state of the art proton therapy system, especially when repainting technique is

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* Corresponding author.
E-mail address: bin.qin@mail.hust.edu.cn (B. Qin).

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required for moving organs treatment. Based on fast scanning speed of the scanning magnets, the repainting technique has been proven to be very effective to mitigate the uncontrolled dose inhomogeneity and the increase of lateral dose conformation due to organ motion [7,8].

Compared to using two scanning magnets, adopting combined X-Y scanning magnet is an effective solution to save spaces. Some designs have been proposed and implemented, such as a novel combined X-Y beam scanning magnet based on cosine current distribution with normal conducting coils [9]. Employing high-temperature superconducting coils can further improve the compactness of the combined magnet [10]. While the implementation of a combined scanning magnet requires precisely symmetric assembly and high current density of the coils, which will increase the difficulty of the fabrication and installation. Considering the technique maturity, separate scanning magnets for two directions are adopted in our design. However, optimizations on the coils and the magnet structure design should be performed.

Eddy current effect is an important issue in design of fast scanning magnets. There are two effects caused by eddy currents [11]. One is the heating of the magnet, and other is the hysteresis effect of the magnetic field. These effects limit the operation frequency and the implementation of the fast energy switching. Some method should be used to reduce the temperature rise of the magnet and the lag effect due to eddy currents should be evaluated. This paper describes the design considerations of scanning system and two scanning magnets, and mainly analyzes eddy current effect and temperature rise of the magnets. Based on electromagnetic and thermal analyses, an optimized design of scanning magnets will be given.

2. Physical consideration of the scanning system

Fig. 1 shows the layout of the gantry beamline of HUST-PTF, which is designed for a 360 degrees rotating gantry. B1 and B2 are two 60 degrees dipoles, and B3 is a 90 degrees dipole with a 20 degrees exit angle for better control of the vertical beam envelope. Two sets of BPMs and X/Y steering magnets are configured for beam alignment. For pencil beam scanning, the scanning system consists of a pair of orthogonal dipole magnets: ScMX and ScMY, in which ScMX is responsible for fast scanning in the first dimension. For physical parameters design, the radiation field size, the SAD and the scanning speed are taken into considerations under overall scanning system.

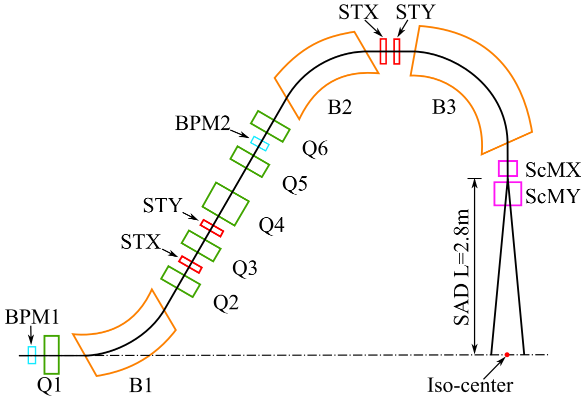

Fig. 1. The layout of the rotating gantry and the illustration of the SAD length.

Radiation field size: From clinical point of view, larger field size will cover more tumour categories without pitching technique. However, this parameter is limited by the maximum deflection angle of the scanning magnets and SAD. Also a moderate excitation current should be adopted for maximum deflection angle, to avoid the field inhomogeneity which will influence the linearity of the beam position. The field size 30×30 cm^2 is designed for HUST-PTF, when taking the clinical demands and economic factors into considerations.

SAD: Approximately, SAD can be defined as the distance from the midpoint of two scanning magnets to the isocenter [12]. For downstream scanning, the range of SAD is 2.0–3.0 m. Short SAD can decrease the radius of the gantry, but it will bring dose increase on the patient's skin due to the unparallel beam. As investigated in PSI [13], when SAD $\geq$2.5 m, only 25% dose increasement were found in the skin for proton beam energy below 200 MeV. To mitigate this side-effect, a 2.8 m length of SAD is adopted for the gantry beamline.

Scanning speed: Spot scanning will be the main treatment mode for HUST-PTF. In this mode, a pencil beam is deflected and transported to the given coordinate in the treatment volume and stays on that point until the prescribed dose is achieved [14]. The scanning speed of the scanning system, the switch on/off time of the beam, and the dose rate are main factors to influence the overall treatment time. For fast scanning magnet ScMX, a maximum operation frequency is designed, corresponding to the maximum beam scanning velocity of 60 mm/ms at the iso-center.

Based on these considerations, Table 1 lists the detailed parameters of two scanning magnets. The gap and pole width of ScMX and ScMY are optimized based on beam trajectory simulations. Small amount of turns of magnet coils with high current are adopted to decrease the coil inductance, which requires the maximum current ramping speed to be up to 228 kA/s, corresponding to a maximum magnetic field time gradient with 208 T/s under 100 Hz operation frequency.

3. Electromagnetic and thermal simulation

3.1. *Eddy currents and heat generation*

In the AC magnet design, eddy currents and heat generation from eddy losses are of great concern. The magnets consists of coils, iron core and two stainless steel (SS) end plates. The iron core is made of 0.1 mm thick silicon steel sheets to reduce the amount of eddy currents and heat losses. Under the AC operation condition, heat generation often comes from four reasons:

(a) Eddy currents in the sheets which flows along the sheet surfaces and thin cross sections.

Table 1
Main parameters of scanning magnets.

Parameters	Unit	ScMX	ScMY
Max Deflection Angle	mrad	55	65
Magnet Gap	mm	40	90
Magnet Pole Width	mm	90	160
Max Field Strength	T	0.52	0.39
Pole Length	mm	230	330
Magnet Length[a]	mm	250	370
Number of coil turn	turns/pole	15	18
Coil Inductance	mH/coil	0.33	0.60
Coil Resistance	m Ohm/coil	2.21	2.74
Repetition Frequency	Hz	100	40

[a] The magnet length refers to the total length of the magnet including the iron core and two end SS plates.